A New Method to Measure Temperature and Burner Pattern Factor Sensing for Active Engine Control

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Acknowledgments

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Introduction

The determination of the temperatures of extended surfaces which exhibit non-uniform temperature variation is very important for a number of applications including the "Burner Pattern Factor" (BPF) of turbine engines. Exploratory work[1] has shown that use of BPF to control engine functions can result in many benefits, among them reduction in engine weight, reduction in operating cost, increase in engine life, while attaining maximum engine efficiency. Advanced engines are expected to operate at very high temperature to achieve high efficiency. Brief exposure of engine components to higher than design temperatures due to non-uniformity in engine burner pattern can reduce engine life. The engine BPF is a measure of engine temperature uniformity. Attainment of maximum temperature uniformity and high temperatures is key to maximum efficiency and long life. A new approach to determine through the measurement of just one radiation spectrum by a multiwavelength pyrometer is possible. This paper discusses a new temperature sensing approach and its application to determine the BPF.

Method

BPF sensing of a combustor is normally obtained[2] from calculation performed on temporal and spatial temperature distributions provided by thermocouple (TC) arrays instrumented at the engine inlet and exit planes according to:

$$BPF(t) = \frac{T_4(x,y,t)_{max} - \overline{T_4(x,y,t)}}{\overline{T_4(x,y,t)} - \overline{T_3(x,y,t)}} \qquad 1$$

$T_3(x,y,t)$ and $T_4(x,y,t)$ are the inlet and exit temperatures. $T_4(x,y,t)_{max}$ is the maximum temperature anywhere in the exit plane. The barred quantity $T_4(x,y,t)$ is the instantaneous spatial temperature average. The needed TC arrays to provide the temperature for BPF calculation are often difficult to instrument. The calculated BPF is then used in active engine control. The quantity in the numerator of Eq. 1 is a crude estimate of σ, the standard deviation of T_4 from its average value. Instead of using point measuring TC arrays to calculate the BPF, the full field viewing (the whole engine) capability of a modified multiwavelength pyrometer[3] offers a new possibility to calculate σ, requiring just a single measurement experiment.

Point measurement of temperatures on a surface using a multiwavelength pyrometer depends on the detection of radiation from a small area according to Planck's law (Eqn. 2)

$$L_\lambda = \varepsilon_\lambda \frac{c_1}{\lambda^5} \frac{1}{\exp(c_2/\lambda T) - 1} \qquad 2$$

where L_λ and ε_λ are the spectral intensity and emissivity at wavelength λ, c_1 and c_2 are the radiation constants, and T is the temperature. The optics of the multiwavelength pyrometer can collect at the same time all signals originating from the surface elements of a large object whose surface temperature varies from point to point. $\Delta a(T)$, is a surface element function which depends on the temperature T. The signal detected by the pyrometer is the integrated intensity of all its surface elements $\Delta a(T)$ of local temperature T given by the integral equation

$$L_\lambda = \frac{c_1}{\lambda^5} \int \frac{1}{\exp(c_2/\lambda T)-1} d\big(\varepsilon_\lambda a(T)\big) \qquad 3$$

This is the remote sensing equation of an area exhibiting a temperature distribution. A single radiation spectrum from a very extensive source, such as a combustor, covering a wide spectral region can be acquired by the multiwavelength pyrometer. This spectrum consists of many radiation components covering a very broad wavelength (spectral) range. The temperature distribution of the radiation emitting surface can be determined from an analysis of this spectrum. The combustor's burner pattern factor is then easily calculated from that temperature distribution as shown below.

Experiment

An experiment was conducted using a metal plate measuring 20 cm in diameter to simulate the engine combustor. The plate was raised in temperature by impinging a narrowly penciled propane torch flame at its surface that is hidden from the view of the measuring pyrometer spectrometer. The flame geometry produced a non-uniform temperature distribution on the metal plate (Figure 1). The spectrometer is part of a commercial radiometer. It was calibrated with a black body furnace and then used to acquire the very broad spectrum of this spatially large, non-uniformly heated, radiating metal plate. This spectrometer has a normal field of view variable from 1 to 6 milli-radian (mR) and is capable of operating in the spectral region between 1.3 and 14.5 μm. The spectrometer is modified by an attachment enabling it to view a much wider (6°) field. The metal plate was completely contained inside the radiometer's increased broader field of view by varying the distance between it and the spectral radiometer. The recorded spectrum is shown in Figure 2.

Result

The analysis of the data is as follows. The region of interest of the temperature space T is from $T = T_0$ to $T = T_m$. By dividing the temperature domain T into m equal intervals, we have $T_j = T_0 + j\,\Delta T$, where $\Delta T = (T_m - T_0)/m$, $j = 0$ to m. A piecewise integration of Eqn. 3 can now be performed. The result

$$L_{\lambda_i} = \sum \frac{c_1}{\lambda^5_i} \frac{1}{\exp(c_2/\lambda_i T_j)-1} \varepsilon_{\lambda_i} a(T_j) \qquad 4$$

discretizes the integral equation into a matrix equation Eqn. 4. The quantity on the left is an n dimensional column vector L connecting the experimental spectrum L_λ, (consisting of n (= 455) wavelength channels of spectral data in the spectrum of Figure 2) to the desired solution function **a**, (an m dimensional column vector, whose elements are a (T_j) in the temperature intervals j = 1 to m), via an n x m dimensional matrix **K**, whose elements K_{ij} are

$$K_{ij} = \frac{c_1}{\lambda^5_i} \frac{1}{\exp(c_2/\lambda_i T_j)-1} \qquad 5$$

It is desirable to solve for the quantities a(T) in Eqn. 3 by solving a matrix equation. Eqn. 4 can now be written as

$$L = K \bullet a \qquad 6$$

The straight forward matrix solution of Eqn. 6 is

$$a = K^{-1} \bullet L \qquad 7$$

The matrix inversion is a class of "ill-posed" mathematical problem, requiring "regularization"[4-5] to determine its solution according to

$$a = \big(K'K + \alpha I\big)^{-1} \bullet \big(K'L + \alpha c\big) \qquad 8$$

where I is the identity matrix, α is a scalar constant, called the regularization parameter, chosen to reduce the noise that accompanies the possible solutions obtainable in the inversion process, and c is a constant matrix. An iteration procedure was employed to solve Eqn. 8. The solution of a is shown in Figure 3.

Apparent in the solution of the spectrum analysis were three distinct temperature distributions centering around 375 K, 680 K and 930 K. The 930 K temperature agreed well with the temperature measured by the multiwavelength pyrometer when it was trained on the glowing hot spot produced by the propane torch on the metal plate. This hottest temperature region was attributed to arise from the direct impingement of the torch flame on the plate. The intermediate temperature region, 680 K, is the result of that part of the metal plate immersed in the updraft of the hot combustion products accompanying the flame. Finally, as a result of heat conduction taking place up to the time the spectrum was recorded, the remainder of the plate temperature had risen to about 75 K above ambient. An average plate temperature of 567 K was calculated from the temperature distribution according to

$$\bar{T} = \frac{\sum T_i a(T_i)}{\sum a(T_i)}$$

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Treating the metal plate as the combustor, with T_3 taken to be 300 K, then according to Eqn. 1, the BPF is 1.36. In the mathematical formulation of Eqn. 3 to analyze the spectrum, though the surface emissivity was explicitly shown, it did not enter into the analysis. During the digitization of the integral equation into a matrix equation, the emissivity and the integrating element are lumped together. This incorporation did not affect the independent variable T in the equation.

Conclusion

Pyrometric determination of surface temperature distribution was demonstrated. A radiation spectrum from a heated metal surface was used. Analysis of the radiation spectrum led to the formulation of an ill-posed matrix equation problem, whose solution provided the temperature distribution for burner pattern factor calculation. The spectrometer of a multiwavelength pyrometer was the instrument used to measure the radiation spectrum, and off-the-shelf commercial software tools were used to perform the mathematical analysis.

Acknowledgement

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1.   Uncirculated result of SBIR contract by the Physical Sciences Inc (NAS3-27590) and by Allied Signal Engine Company.
2.   Acosta, Waldo. A., Introduction to Combustors, NASA Lectures, Sep 8, 1988.
3.   Ng, Daniel, Temperature Measurement of a Glass Material Using a Multiwavelength Pyrometer, NASA TM 107433, 1997.
4.   Craig, I.J.D., Brown, J.C., Inverse Problems in Astronomy, Adam Hilger Ltd, Bristol and Boston.
5.   Ohno, Jiro, A New Method for Temperature Distribution Measurement Using Multi-spectral Radiance, Temperature, Its Measurement and Control in Science and Industry, Volume Five, James F. Schooley, Editor, page 401-407, 1982.

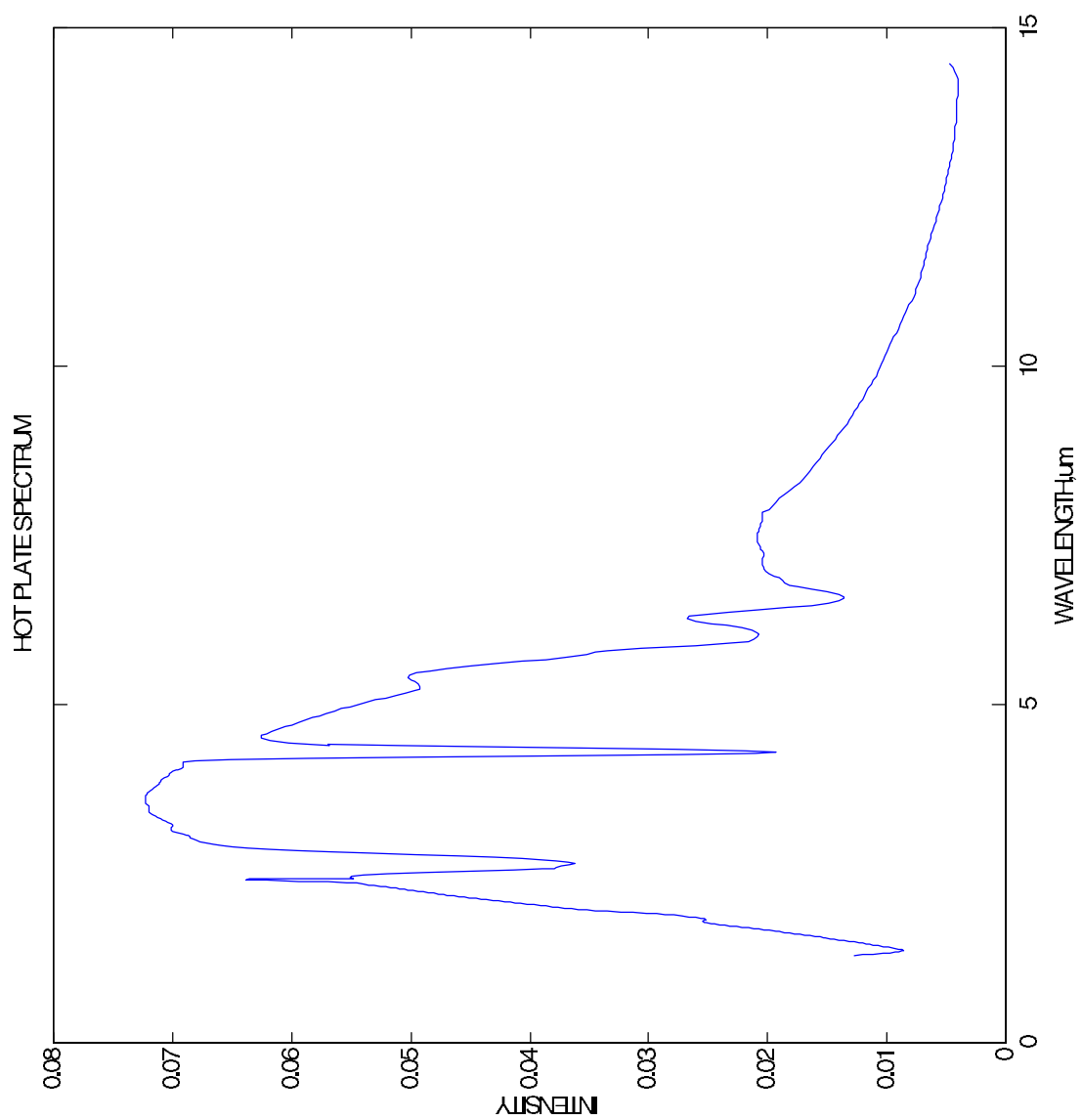Figure 1   Metal plate heated by a propane torch.

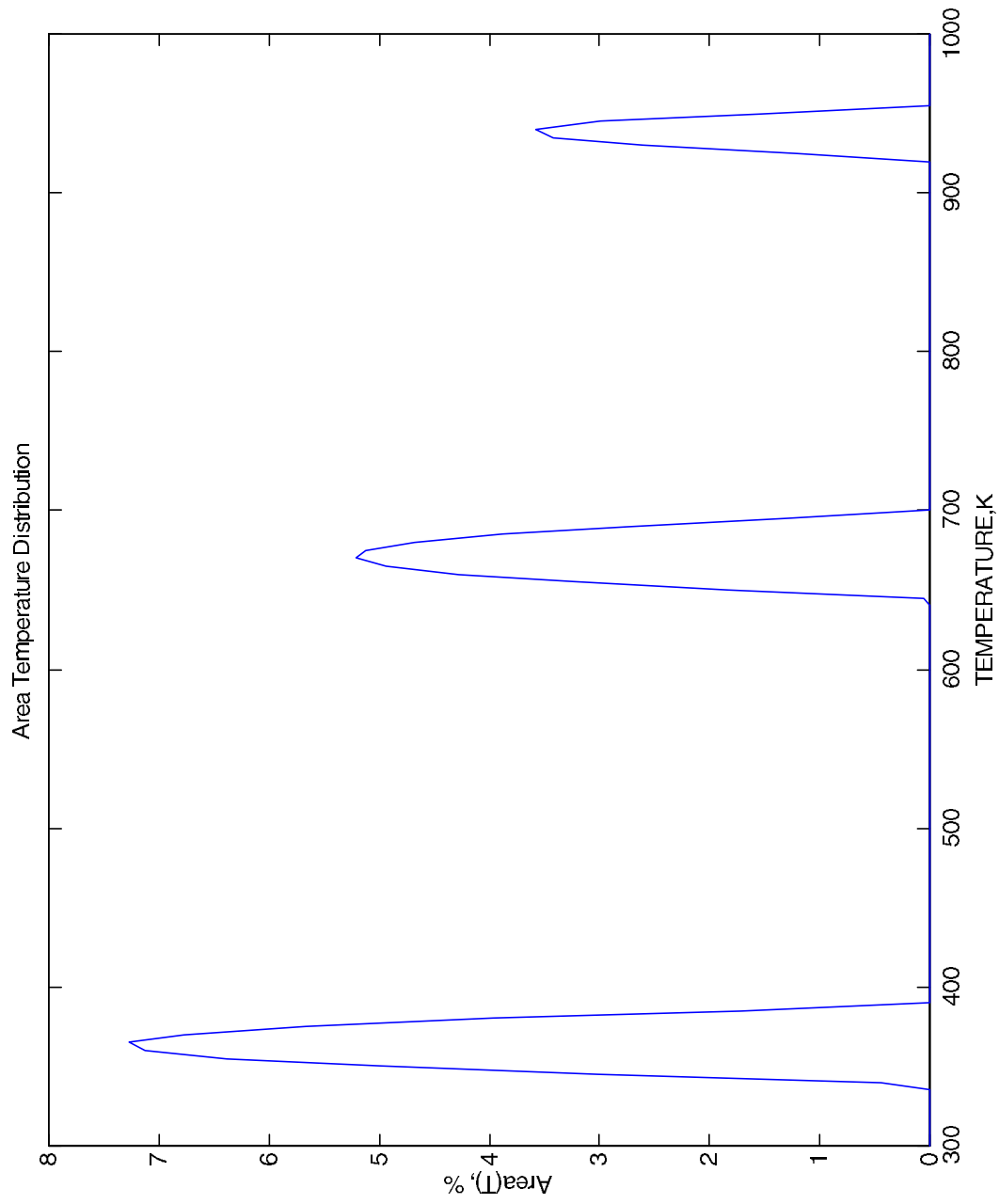Figure 2   Spectrum of propane torch heated metal plate

Figure 3   Solution of Temperature Distribution

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